ARTIFICIAL NEURAL NETWORKS AS APPLIED TO AIRCRAFT FLIGHT TEST PLANNING

WYKORZYSTANIE SZTUCZNYCH SIECI NEURONOWYCH W PLANOWANIU BADAŃ W LOCIE

Mirosław Zieja, Joanna Wójcik

Air Force Institute of Technology, Poland

Abstract: Any flight test programme is essentially based on a flight test plan, i.e. a document agreed upon and accepted by all the parties interested in the tests, and authorised by the superior body/authorities responsible for the execution of the tests. The flight test plan determines the number of flights and flight hours indispensable to verify whether a given aircraft satisfies specified requirements. Many and various external factors may have significant and adverse effect on the execution of the flight test program according to the earlier agreed schedule.

The study also covers the structure of a model of a management system for aircraft prototype testing, and the structure of artificial neural network (ANN) developed on the basis of experimentally gained data from the military aircraft testing. A mathematical model based on the artificial neural network and its potential for the managing of aircraft prototypes testing has been formulated as well.

Keywords flight test planning, flight test schedule,, artificial neural networks

Streszczenie: Podstawą merytoryczną przeprowadzenia każdego rodzaju badań w locie jest program badań (testów) – dokument posiadający uzgodnienia wszystkich stron zainteresowanych badaniami oraz zatwierdzony przez organ nadrzędny odpowiedzialny za realizację tych badań. Program badań zawiera liczbę lotów i liczbę godzin lotu jaka jest niezbędna do oceny zgodności danego statku powietrznego z wyspecyfikowanymi wymaganiami. Wiele czynników zewnętrznych ma negatywny wpływ na realizację programu badań zgodnie z ustalonym harmonogramem.

W niniejszym opracowaniu zaprezentowano strukturę modelu systemu zarządzania badaniami prototypów statków powietrznych, jak również strukturę sztucznej sieci neuronowej opracowaną w oparciu o doświadczalnie zgromadzone dane z badań wojskowych statków powietrznych. Przedstawiono model matematyczny oparty na SSN i możliwość jego potencjalnego wykorzystania w zarządzaniu badaniami prototypów statków powietrznych.

Słowa kluczowe: planowanie badań w locie, program badań, sztuczne sieci neuronowe

1. Introduction

The primary objective of flight tests is to validate the aircraft conformity with requirements listed in technical specifications, rules and regulations on aircraft building, standards, and Customer's requirements.

The accuracy of the FT programmes and proper execution thereof strongly affects the capability to keep to the required safety levels while operating the aircraft.

The following items are determined in the course of the aircraft flight testing:

- physical and functional characteristics;
- to what degree the aircraft subjected to flight tests meets the specification-defined requirements;
- the aircraft's suitability to perform specific missions in the future;
- the correctness of applied solutions: aircraft design, maintainability, damageability, and flight safety regimes in the course of aircraft operation;
- aircraft handling qualities and performance characteristics;
- the correctness of operation of newly-built-in devices and systems;
- the assessment of aircrew personal/group items of equipment supposed to provide operational use and maintenance of the aircraft;
- validation of the standard for the already existing aircraft to be upgraded and/or to put aircraft from the initial-production stage to the lot production;
- compliance of the prototype characteristics with requirements and determination of capabilities of introducing the aircraft into inventory and then into the market (lot production);
- compliance of the product (aircraft, equipment) with requirements of the technical specification and the standard;
- recommendations on combat applications of the device/system/product;
- the assessment and updates of the technical specification;
- causes of aircraft failures, determination of preventive treatment.

The output documents produced in the course of the planning include the flight test (FT) programme together with the flight test (FT) schedule and methodology. These are the substantive and organisational documents that form the basis for the execution of flight trials.

The FT programme usually covers the following issues:

- identification of the object to be put to tests;
- the reference documents that form the basis for the execution of trials;
- the scope of the testing work (tasks) to be done and aims to be reached;
- organizational and engineering arrangements for the intended testing work;
- testing conditions and procedures;
- requirements for reporting.

The FT schedule which is a plan of flight trials execution over a specific period of time is an integral part of the FT programme. Account is taken of the availability of labour and resources, climatic conditions and other factors that may affect the

execution of the trials, such as predispositions of flight test team members, their proficiency, etc., with flight test safety taken into consideration.

While developing the FT programme and with the above-mentioned issues taken into account, one has to give careful consideration to the following items, among many other:

- 1) Customer's requirements on the scope of flight tests;
- 2) time limit/closing date of the execution stage;
- 3) the Customer-assumed (cost-related) number of flights;
- 4) funds pre-planned by/available to the Customer to develop and execute the flight test programme;
- 5) the assumed parameters that allow of the operational use and maintenance of the aircraft according to technical/time-based characteristics given in the technical documentation;
- 6) the assumed parameters of the test-subjected object's resistance to damage;
- 7) the testing site (appointed airfield, flight-test area):
 - geographic location;
 - the structure of weather conditions over the time planned for the execution of flight tests.

Below presented is an exemplary analysis of how the number of flying hours depend on the date of performing the tests.

Depending on the Customer-imposed date, portions of daytime available to perform flight tests differ (Fig. 1).

Fig. 1. Distribution of flying hours in the daytime in particular months

The distribution of flying hours throughout the daytime for different seasons of the year is of great importance to the planning of flight tests if the Customer has specified the time of interest to them.

Also, the presented curves allow of the selection of optimum time of flight-test execution in the aspect of the duration of tests and hence, the cost.

Another analytical example is the dependence of the number of days suitable for aircraft flight testing on the Customer-indicated test site (Fig. 2).

*Fig. 2. The average number of days with the following weather conditions:
 cloud cover $\leq 6/10$; visibility ≥ 6 km on military airfields
 in various regions of Poland*

With the above given data, estimated is the time indispensable to perform the assumed number of flights depending on both the time period and the site/region selected to perform the tests. While planning the minimum time limit, one should take account of hazards resulting from discrepancies between actual weather conditions, under which the tests will be performed and information from the knowledge base at his disposal on meteorological conditions.

- 8) availability of logistics-support delivered resources;
- 9) flight test team (flight-test manager/engineer, flying staff, flight test instrumentation engineers/technicians, and those to analyse data acquired from the tests):
 - the number of team members,
 - availability of team members,
 - levels of proficiency (knowledge/skill) of particular team members;
- 10) the required measuring equipment, availability thereof;
- 11) experience from the hitherto conducted flight tests:
 - the sequence of the most essential (indispensable) tests,
 - tests to be carried out in sequence or in parallel,
 - the necessity to repeat the test because of either weather conditions or a failure to carry out the test,
 - unreliability of measuring equipment,
 - susceptibility of the aircraft to failure, necessity of fault clearing,
 - unforeseen events,
 - etc.

With the database on already completed flight tests of aircraft at hand, the randomly occurring elements that proved hazardous to the execution of flight test programmes (the so-called random instances) are analysed. The following belong to this group:

- 1) the need for the tests to be repeated, resulting from the following facts:
 - preparations for the test flight have not been completed (e.g. equipment to be flight tested, measuring systems/devices, externally carried payload have not been installed, no weapon systems, indispensable aircraft/aircraft systems' maintenance has not been performed);
 - an in-flight change in weather/meteorological conditions occurred;
 - the test flight has not been performed/completed according to the test flight programme due to, e.g. the pilot error;
- 2) a shortage of pilots highly skilled at performing test flights (because of, e.g. an unexpected illness, earlier scheduled trainings, or an unexpected call to perform operational mission(s) at his/her mother air base);
- 3) the earlier flight remaining uncompleted;
- 4) extra flight(s) provoked additional routine, periodic, and special-purpose maintenance while flight testing the aircraft;
- 5) occurrence of failures that make additional flights indispensable;
- 6) organization/planning-attributable errors (e.g. insufficient quantities of emergency/rescue equipment, no other aircraft to follow the flight-tested one, high-altitude/rescue equipment, shortage of spare parts to replace failed items of the test equipment, insufficient number of computers to analyse flight-tests delivered data, etc.).

The conducted analyses of the required tests, conditions to perform these tests, and experience already gained provide the basis for the determination of: the number of flights, the number of flight hours, the time necessary to evaluate the aircraft at the assumption that all factors which might have had some effect upon the flight test execution do not influence the work negatively.

The process of developing both the FT programme and the FT schedule is an extremely difficult job because of, among other things, high complexity of factors to be taken into account. Successful completion of this job needs extremely wide knowledge and rich experience.

The Authors have suggested the application of neural networks to optimally plan the flight-test programme according to the Customer's requirements, at a proposed cost, and with safety of both the staff and the aircraft provided.

2. A model to support management of flight testing of prototype aircraft

In practice, it is impossible to present all the factors that affect reliability of aircraft testing since the complexity of any aeronautical system is extremely high. However, all the processes and preventive undertakings are aimed at the increase in reliability of such testing work.

The in the paper suggested model to support management of flight testing of prototype aircraft will comprise the following items:

- determination of time period required to perform flight testing of prototype aircraft, and
- artificial neural network (ANN) design to support management of flight testing of prototype aircraft.

The first stage of the whole process is usually intended for the recognition of reliability of particular tests; also, estimated is time needed to complete the tests.

The intended purpose of the second stage is to find an optimum sequence of tests to be carried out.

The ANN structure of the flight-test management model for prototype aircraft

The accretion of unrealised flight tests of aircraft is a stochastic process. Nevertheless, it is obvious that the intensity of generating unrealised tests is directly proportional to both the intensity of the flight-test conduct and the rate of unrealised tests, and inversely proportional to the rate of learning (e.g. effectiveness of preventive treatment applied). Hence, the intensity of the unrealised test occurrences takes the form:

$$\gamma(t) = \frac{\alpha\lambda}{1+\beta t} \quad (1)$$

where:

- α - the intensity of conducted flight tests,
- t - the planned time for conducting the tests,
- λ - the rate of unrealised tests,
- β - the rate of learning (e.g. effectiveness of preventive treatment applied in the course of tests).

Furthermore, the probability that the number of unrealised tests within the test-dedicated time interval Δt increases, satisfies the following relationship:

$$\gamma(t)\Delta t \leq 1 \quad (2)$$

With the function of intensity of generating unrealised flight tests determined in this way, one can describe reliability of performing flight tests using difference equations. Therefore, let us first describe the dynamics of the increase in number of unrealised tests. Let $U_{k,t+\Delta t}$ denote the probability of the k number of unrealised tests up to time instance t throughout the whole process of performing flight tests.

Hence, the dynamics of the increase in number of unrealised tests can be described with the following equation:

$$U_{k,t+\Delta t} = (1 - \gamma(t)\Delta t)U_{k-1,t} \quad (3)$$

where: k - the number of tests unrealised up to time instance t ,

$\gamma(t)$ - function of intensity of generating unrealised tests, equation (1).

Equation (3) takes the following form with the function notation applied:

$$U(k, t + \Delta t) = (1 - \gamma(t)\Delta t)U(k, t) + \gamma(t)\Delta tU(k - 1, t) \quad (4)$$

Let us rearrange the difference equation (4) in a partial differential equation. From equation (4), with the Taylor formula applied for $n = 2$ and $n = 1$, a partial differential equation is arrived at. The rearrangement of equation (4) in a partial differential equation proceeds in the following way, with the following approximations assumed:

$$u(k - 1, t) = u(k, t) - \frac{\partial u(k, t)}{\partial k} + \frac{\partial^2 u(k, t)}{2\partial k^2} \quad (5)$$

$$u(k, t + \Delta t) = u(k, t) + \frac{\partial u(k, t)}{\partial t} \Delta t$$

Substituting relationships (5) into (4) the following dependence is arrived at:

$$u(k, t) + \frac{\partial u(k, t)}{\partial t} \Delta t = (1 - \gamma(t)\Delta t)u(k, t) + \gamma(t)\Delta t(u(k, t) - \frac{\partial u(k, t)}{\partial k} + \frac{\partial^2 u(k, t)}{2\partial k^2})$$

Hence,

$$\begin{aligned} \frac{\partial u(k, t)}{\partial t} \Delta t &= -\gamma(t)\Delta t \frac{\partial u(k, t)}{\partial k} + \frac{1}{2}\gamma(t)\Delta t \frac{\partial^2 u(k, t)}{\partial k^2} \\ \frac{\partial u(k, t)}{\partial t} &= -\gamma(t) \frac{\partial u(k, t)}{\partial k} + \frac{1}{2}\gamma(t) \frac{\partial^2 u(k, t)}{\partial k^2} \end{aligned} \quad (6)$$

To present solution to equation (6), the Fokker-Planck equation of the following form has been used:

$$\frac{\partial \bar{u}(k, t)}{\partial t} = -b \frac{\bar{u}(k, t)}{\partial k} + \frac{1}{2}a \frac{\partial^2 \bar{u}(k, t)}{\partial k^2} \quad (7)$$

Now, we have to look for a particular solution to equation (7) such that for $t \rightarrow 0$ it is convergent to the so-called Dirac delta function, i.e. $\bar{u}(k, t) \rightarrow 0$ for $k \neq 0$ and $\bar{u}(k, t) \rightarrow +\infty$, in such a way, however, that the function integral $\bar{u}(k, t)$ equals unity for $t > 0$.

For the above formulated condition, the solution to equation (7) takes the following form:

$$\bar{u}(k, t) = \frac{1}{\sqrt{2\pi at}} e^{-\frac{(k-bt)^2}{2at}} \quad (8)$$

Since function (7) is the solution to equation (8), the solution to equation (6) can be presented in the following form:

$$u(k, t) = \frac{1}{\sqrt{2\pi A(t)}} e^{-\frac{(k-\beta(t))^2}{2A(t)}} \quad (9)$$

where:

$$A(t) = \int_0^t \gamma(t) dt = \alpha \lambda \int_0^t \frac{dt}{1 + \beta \alpha t} = \alpha \lambda \left(\frac{1}{\beta \alpha} \ln(1 + \beta \alpha t) \right)$$

$$A(t) = \frac{\lambda}{\beta} \ln(1 + \beta \alpha t) \quad \text{for } \beta \geq 1 \quad (10)$$

$$B(t) = A(t)$$

Function (9) shows characteristics of the density function, since:

$$\int_{-\infty}^{\infty} \int_0^{\infty} u(k, t) dk dt = 1$$

An artificial neural network (ANN) design to support management of flight testing of prototype aircraft

With the in this way found rates (equation 10) one can set about formulating the ANN model. Let the set A denote all available aeronautical tests. Therefore, a single 'package' of tests can be defined as the set B:

$$B = \{B_1, B_2, \dots, B_n\},$$

where n stands for the number of tests in a package. Naturally, the set B is contained in the set A. Then, to any test the unreliability (unrealisability) rate for this particular test and time period to complete this test are assigned.

$$\forall_{i=1}^{i=k} B_i \rightarrow \lambda_i, B_i \rightarrow t_i.$$

With the in this way found rates, one can set about formulating the ANN model.

Fig. 3. The ANN model

Neurons are formed from components of the set B. A single artificial neuron is defined as a k -component permutation of the set B. Hence, let the set C be a set of all neurons.

$$C = \{C_1, C_2, \dots, C_k\}$$

What results is an estimate of time needed to complete the test. This estimate is found using **equation 10**.

$$V_{i \in (1,k)} C_i \rightarrow T_i.$$

The next step is to process the neurons using the activation function (AF):

$$FA = \min\{T_i\} \text{ dla } i \in \langle 1, k \rangle$$

At the output, a single neuron is gained. It is composed of aeronautical tests arranged in some appropriate sequence. The process of teaching the network consists in forming rates β (the ANN learning) for each aeronautical test in a given month.

Tabel 1. A set of the network learning rates

Number of Tests /Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
A_1	$\beta_{1,1}$	$\beta_{1,2}$	$\beta_{1,3}$	$\beta_{1,4}$	$\beta_{1,5}$	$\beta_{1,6}$	$\beta_{1,7}$	$\beta_{1,8}$	$\beta_{1,9}$	$\beta_{1,10}$	$\beta_{1,11}$	$\beta_{1,12}$
A_2	$\beta_{2,1}$	$\beta_{2,2}$	$\beta_{2,3}$	$\beta_{2,4}$	$\beta_{2,5}$	$\beta_{2,6}$	$\beta_{2,7}$	$\beta_{2,8}$	$\beta_{2,9}$	$\beta_{2,10}$	$\beta_{2,11}$	$\beta_{2,12}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
A_n	$\beta_{n,1}$	$\beta_{n,2}$	$\beta_{n,3}$	$\beta_{n,4}$	$\beta_{n,5}$	$\beta_{n,6}$	$\beta_{n,7}$	$\beta_{n,8}$	$\beta_{n,9}$	$\beta_{n,10}$	$\beta_{n,11}$	$\beta_{n,12}$

The algorithm of creating the rates comprises the following stages:

- loading a ‘package’ of tests into the network (including the day/date of starting/terminating the tests) – stage I;
- selection of suitable neurons and determination of the advancement of particular components of a single neuron (this is to be done by the User with an expert method applied) – stage II;
- selection of the optimum neuron (this is also to be done by the User with an expert method applied) – stage III;
- **equation (10)**-based forming, by the network, of suitable rates β , in such a way as to have the time for the neuron creation shorter than that for performing a test (stage III) and with stage II proceeding.

It should be noted that under comparable conditions (i.e. with readiness of both the pilot and the aircraft) the rate α (intensity of aeronautical tests) takes the following value:

$$\alpha = 1.$$

3. Software-oriented implementation of the method as illustrated with the SYMBAD application

The SYMBAD 2012/2013 program has been developed under the Borland C++ Builder programming environment. It uses an innovative approach to any issues of the aeronautical testing and is a practical manifestation of theoretical considerations given above.

Four modules can be distinguished in the SYMBAD 2012/2013 program. They are as follows:

- a module to teach the neural network,
- a module to predict time needed for aeronautical tests,
- a module to generate global settings of the program,
- a module to select aeronautical tests.

The first module consists in loading exemplary sets of tests and results thereof into the program. On the basis of these results and the global settings the program generates estimates of time needed to accomplish the selected tests.

The global settings of the SYMBAD 2012/2013 program may refer to:

- the pilot data,
- flyable days in particular months,
- flyable hours in particular months.

The program may also deliver a printout with the set of tests and predictions on time needed to accomplish these tests.

Presented below are application windows of the SYMBAD 2012/2013 program.

Fig. 4. The SYMBAD main menu and the selection of tasks from the 'Oblot' ('Test flight') menu

Fig. 5. The 'Wczytaj' ('Download') option, 'Zapisz' ('Store') data in the 'Plik' ('File') menu

Fig. 6. The 'Number of flyable hours in subsequent months' setting

Fig. 7. Selection of tests from the 'Prędkość lotu' ('Flight speed') menu

Fig. 8. The module to forecast the testing time in the SYMBAD program

4. Conclusions

What has been discussed in the paper is a very special nature of planning the aircraft flight testing. Presented is the complexity of the process of flight test planning attributable to the nature of the object to be tested, organisational principles that underlie the flight testing practice, and the need of several flight testing teams to collaborate.

As the analyses of FT programmes and flight testing practice following the FT programme show, it sometimes happens that the FT programme is not executed exactly in conformity with the assumptions made.

The special nature of aircraft flight testing along with the complexity of objects put to tests, participation of many and various flight testing teams, the diversity of issues of logistics support, as well as external conditions make that the FT planning requires rich experience of all the staff responsible for that area of activity, and of the teams that collaborate on the FT programme. Ability to predict and that to assess any hazards that may occur are another musts.

Apart from respecting the Customer's needs and the documents of reference currently in force, this is why the FT planning is in great part based on rich experience of all the researchers taking part in the FT programme.

The above-presented model of an artificial neural network (ANN) makes use of rich experience gained by the FT staff during the flight testing work in the course of network teaching. It is also an excellent tool to support the FT planning, and allows of the FT optimisation depending on the pre-defined time, cost, and available resources.

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Dr inż. Joanna Wójcik, doktor nauk technicznych w dyscyplinie budowa i eksploatacja maszyn. Pracownik Instytutu Technicznego Wojsk Lotniczych (ITWL). Współautor wdrożonego systemu zarządzania w ITWL bazującego na zasadach zarządzania przedsiębiorstwem. Nadzoruje funkcjonowanie systemu zarządzania zgodnego z wymaganiami dokumentów standaryzacyjnych NATO serii AQAP, norm ISO 9100, 9001, 17025 oraz przepisów prawnych dotyczących wytwarzania i obrotu wyrobami o przeznaczeniu wojskowym. Autorka wielu publikacji i wystąpień na konferencjach międzynarodowych i krajowych.

PhD. Mirosław Zieja, graduated from University of Lodz in 2004. M.Sc. in Mathematics specialized in Informatics. Since 2004 IT specialist in Air Force Institute of Technology. Participated in the development and implementation of the TURAWA system.